Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 36 (2012) 1631 – 1636

Physics Procedia

Superconductivity Centennial Conference

An explanation for bends of 1-dimensional nanorods

Masashi Mukaida[1], Ataru Ichinose[b], Paolo Mele[c], Kaname Matsumoto[d], Shigeru Horii[e], Yutaka Yoshida[f]

[a]Kyushu University, Motooka 744, Nishi-ku, Fukuoka, Fukuoka. 819-0395 Japan
[b]Central Research Institute of Electric Power Industry, Nagasaka, Yokosuka, Kanagawa, 240-0196 Japan
[c]Hiroshima University, Kagamiyama 1-4-1,Higashihiroshima, Hiroshima, 739-8527 Japan
[d]Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu, Fukuoka, 804-8550 Japan
[e]Kochi University of Technology, Kami, Kochi, 782-8502 Japan
[f]Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603 Japan

Abstract

Growth of artificial pinning centers (APCs) in $YBa_2Cu_3O_{7-\delta}$ (YBCO) films are discussed. The APCs used in this research are $BaZrO_3$ and $BaSnO_3$ nanorods which are reported by Mele *et al.* TEM images show these nanorods gradually bend accordingly with approaching to a surface of films. This feature showed a growth pattern like a firework. We explain the feature of the nanorods as follows; At an early growth stage, films grow in a layer by layer growth mode. The surface of the films is flat and very smooth. After the early growth stage, the film surface gradually becomes rough, indicating the film grows in a Stranski-Krastanov growth mode. This roughness was caused by a spiral growth of films with many steps. At the step of YBCO films, nanorod materials such as $BaZrO_3$ are supplied from one direction. Then, the center of nanorods sifts to the same direction of the step flow. Then, the nanorods bend to the edge of the grains in the films. As a grain in spiral growth had a convex surface, nanorods bent to the direction perpendicular to the grain surface. Finally, nanorods in rough grains form firework structures.

© 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of the Guest Editors.
Open access under CC BY-NC-ND license.

Keywords: Keywords: nanorods \sep PLD \sep $BaZrO_3$ \sep $BaSnO_3$ \sep $BaNb_2O_6$

1. Introduction

High critical temperature superconductors (HTSs) are very promising materials, because, no other materials can feed electrical currents without energy dispersions at as high as a liquid nitrogen temperature. However, HTSs have anisotropic crystal structures as well as transport properties[1, 2]. Critical current density (J_C) of high T_C superconducting films is relatively lower than that of low T_C metal superconductors in magnetic fields. In order to apply high T_C superconductors for power applications, J_C's in magnetic fields must be as high as those of metal superconductors.

The c-axis oriented $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films for coated conductor applications have anisotropic behaviors of J_C in magnetic fields[3]. The J_C in a magnetic field of $\boldsymbol{B}$ parallel to the c-axis of YBCO is much lower than that in a magnetic field of $\boldsymbol{B}$ parallel to the a/b-axis of YBCO[4]. Then the most important subject to be achieved is increasing J_C of high T_C superconductors in a magnetic field of $\boldsymbol{B}$ parallel to the c-axis. Many papers have appeared for the introduction of artificial pinning centers[5, 6, 7, 8, 9].

1875-3892 © 2012 Published by Elsevier B.V. Selection and/or peer-review under responsibility of the Guest Editors.
Open access under CC BY-NC-ND license. doi:10.1016/j.phpro.2012.06.320

Recently, Mele et al. reported ultra high flux pinning properties of $BaZrO_3$ and $BaSnO_3$ doped YBCO thin films[10]. In the report, nanorods grow straight at the early growth stage, and then bend gradually. The bending curvature strongly affects J_C of the films. Then control and understanding of the bending is one of the most important issues. However, there are no explanations for the bending.

In this paper, we discuss the bending of nanorod growth from growth mode of YBCO films.

2. Experimental

YBCO films with $BaZrO_3$ (BZO) nanorods and those with $BaSnO_3$ (BSO) nanorods were grown by pulsed KrF excimer laser deposition using YBCO + 4 wt% BZO and YBCO + 4 wt% BSO targets, respectively. An oxygen partial pressure of 200 mTorr, laser energy of 340 mJ/pulse on $SrTiO_3$ substrates and a substrate temperature of 800 °C were used to deposit all the YBCO films. Thickness of the films are roughly 1μm.

Cross-sectional transmission electron microscope samples are fabricated by using a focused ion beam micro-sampling technology. The lattice images of the films were observed by a transmission electron microscopy (TEM). Grains and their grain size are observed by an atomic force microscope (AFM).

3. Results and discussion

Obtained YBCO films are c-axis oriented. Details of J_C properties of the films are reported elsewhere[10]. We examined the TEM images of nanorods in YBCO films. Figure 1 shows (a) a planar view TEM image and (b) a cross-sectional TEM image of the films. From Fig. 1(a), we can find fireworks with diameters of 200 nm-500 nm. From Fig. 1(b), nanorods are straight at the early growth stage, and gradually bend away from the center.

Next, we look into a one firework in the planar view TEM image. Figure 2 shows a magnified planar view TEM image of a firework. At the center of the firework, there exists a straight nanorod. Length of

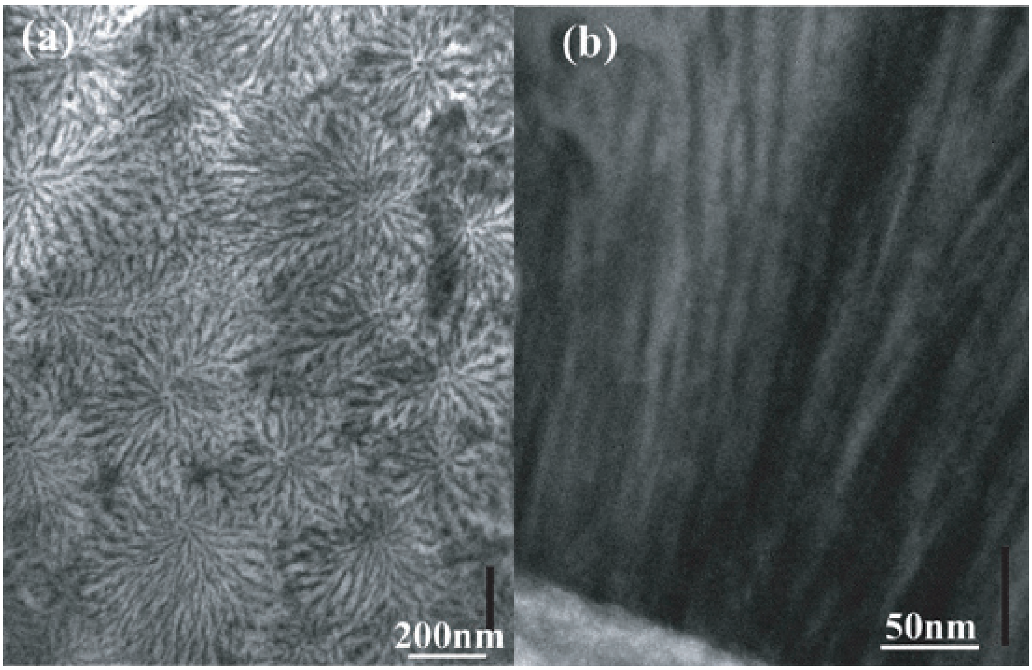

Fig. 1. (a) a planar view TEM image and (b) a cross-sectional TEM image of the films.

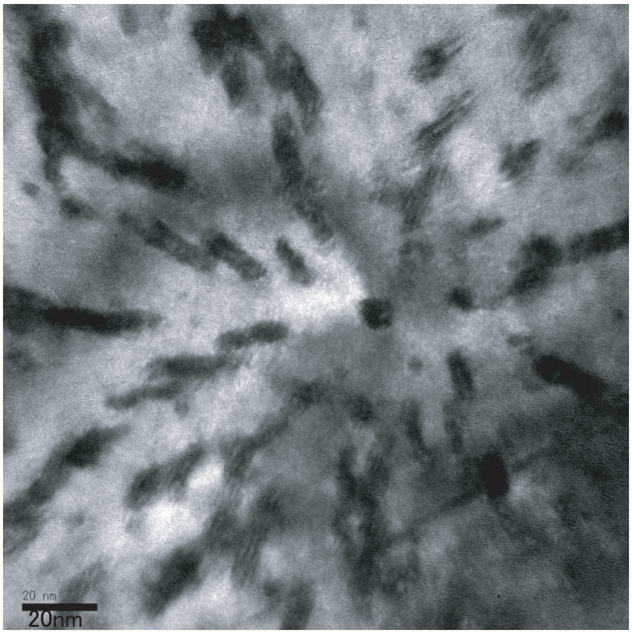

Fig. 2. A magnified planar view TEM image of a firework.

nanorods is seen to be longer at the edge of the firework than that at the center of the firework in the TEM image. It means bending angle of nanorods from a perpendicular line to the substrate surface is large at the edge of the firework. Some nanorods around the center of the firework almost aligned along the neighbor nanorods to the edge of the firework. It means nanorods like to grow above nanorods.

Next we will discuss about formation of firework structures. We focus on diameter of a firework and grain size of the films. From Fig. 1(a), fireworks have diameters around 200 nm-500 nm as mentioned

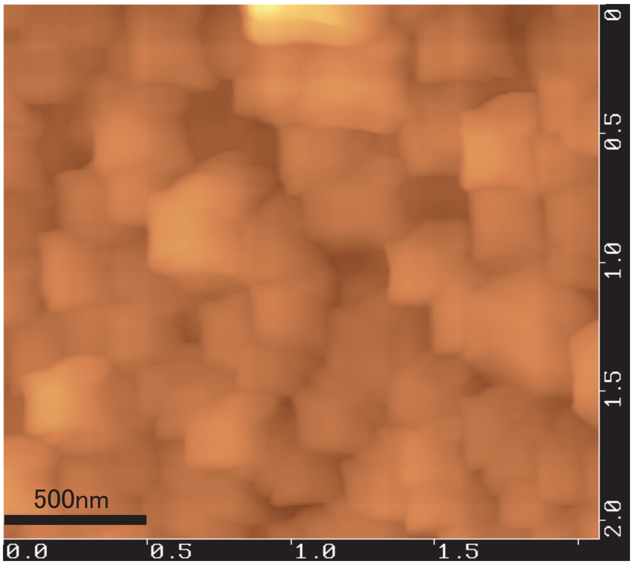

Fig. 3. A typical 2μm square AFM image of YBCO films.

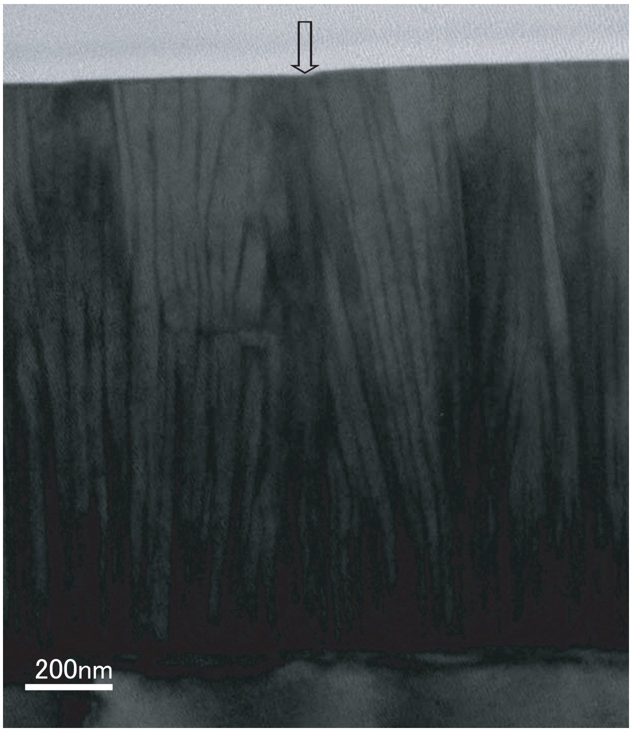

Fig. 4. A magnified cross-sectional TEM image of the film at the surface. An arrow shows a step which is caused by a difference of height between grains.

above. Figure 3 shows a typical 2μm square AFM image of YBCO films. Grain size is almost the same size as that of fireworks around 200 nm-600 nm.

We investigate cross-sectional TEM images as shown in Fig. 4. We can find a step on the surface of the film as indicated by an arrow. Beneath the step, nanorods from two adjacent fireworks meet each other. Then the boundary of fireworks is thought to be a boundary of grains. The step is a difference of height between grains. Consequently, one firework is thought to be composed of nanorods grown in one grain.

Next we explain the bending of nanorods in a view point of growth of YBCO thin films. YBCO films grow in a stranski-krastanov mode[11]. In a stranski-krastanov mode, YBCO films grow in a layer by layer

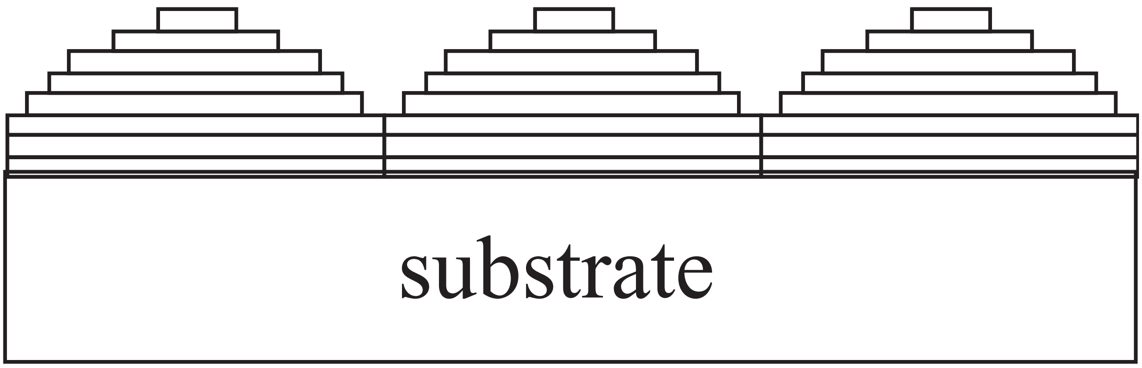

Fig. 5. A schematic drawing of a Stranski-Krastanov growth mode.

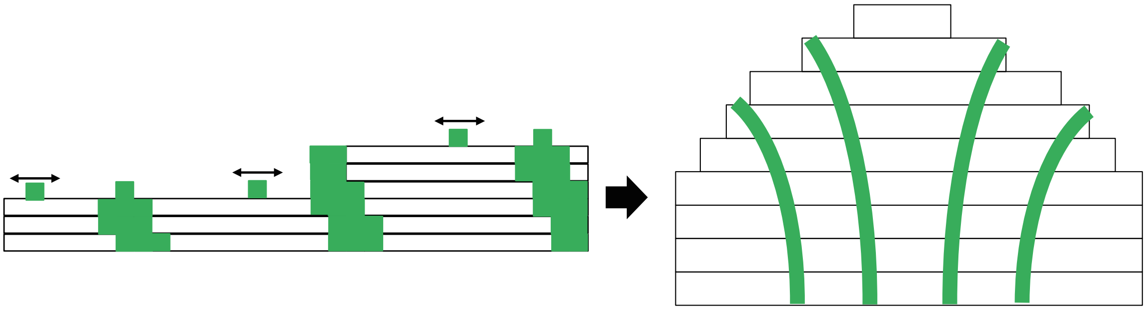

Fig. 6. A schematic drawing of bending growth of nanorods in a convex grain. At the flowing steps of the grains, nanorod materials such as $BaZrO_3$ and/or $BaSnO_3$ are supplied to the nanorods from one direction.

mode at an early growth stage. After the layer by layer mode, the film surfaces change to island growth with rough surface and form grains as shown in Fig. 5. Usually, grains of YBCO with rough surface are high at the center when the films become thick. Typically, these grains have a spiral dislocation at the center. These spirals have many steps at the surface. The steps flow from the center of the grain to the edge of the grain as the film grows. At the flowing steps of the grains, nanorod materials such as $BaZrO_3$ and/or $BaSnO_3$ are supplied to the nanorods from one direction. Because the other side of nanorods are covered by the YBCO steps. Then, the center of nanorods sifts to the same direction of the step flow. It means nanorods are also step flow when the steps of YBCO film come.

Figure 6 shows a schematic drawing of flowing steps and nanorods on the left and final feature of the nanorods in the grains are indicated on the right. From the above considerations, the straight nanorod as shown in the center of the firework of Fig. 2 maybe the nanorod grew close to the center of the spiral dislocation. This growth mechanism is very similar to the eutectic cell growth of Sn-Ca alloys[12]. We believe bends of nanorods are caused by tilted surface of YBCO grains with step flow growth of YBCO films.

4. Summary

Bending of nanorods grown in REBCO films were discussed according to the stranski-krastanov film growth mode of REBCO films. At an early growth stage, films grow in a layer by layer growth mode. The surface of the films is flat and very smooth. However, after the early growth stage, the film surface gradually becomes rough, indicating the film grows in a Stranski-Krastanov growth mode. This roughness was caused by a spiral growth of films with many steps. At the step of YBCO films, nanorod materials such as $BaZrO_3$ are supplied from one direction. Then, the center of nanorods sifts to the same direction of the step flow. Then, the nanorods bend to the edge of the grains in the films. As a grain in spiral growth had a convex surface, nanorods bent to the direction perpendicular to the grain surface. Finally, nanorods in rough grains form firework structures.

References

[1] L. F. Schneemeyer, J. V. Waszczak, T. Siegrist, R. B. van Dover, L. W. Rupp, B. Batlogg, R. J. Cava, and D. W. Murphy: Superconductivity in $YBa_2Cu_3O_7$ single crystals, *Nature*, **328** (1987) 601-603.

[2] M. Mukaida: Broad resistivity transitions in *c*-axis-in-plane-aligned *a*-axis-oriented $YBa_2Cu_3O_x$ thin-films, *Phys. Rev.*, **B 50** (1994) 7124-7128.

[3] B. Dam, J. M. Huijbregtse, F. C. Klaassen, R. C. F. van der Geest, G. Doornbos, J. H. Rector, A. M. Testa, S. Freisem, J. C. Martinez, B. Säuble-Pümin, and R. Griessen: Origin of high critical currents in $YBa_2Cu_3O_{7-\delta}$ superconducting thin films, *Nature*, **399** (1999) 439-442.

[4] L. Civale, B. Maiorov, A. Serquis, J. O. Willis, J. Y. Coulter, H. Wang, Q. X. Jia, P. N. Arendt, J. L. MacManus-Driscoll, M. P. Maley, and S. R. Foltyn: Angular-dependent vortex pinning mechanisms in $YBa_2Cu_3O_7$ coated conductors and thin films, *Appl. Phys. Lett.*, **84** (2004) 2121-2123.

[5] K. Matsumoto, T. Horide, K. Osamura, A. Ichinose, M. Mukaida, Y. Yoshida, and S. Horii: Enhancement of Critical Current Density of YBCO Films by Introduction of Artificial Pinning Centers due to the Distributed Nano-Scaled Y_2O_3 Islands on Substrates, *Physica C*, **412-414** (2004) 1267-1271.

[6] Y. Shingai, M. Mukaida, K. Matsumoto, Y. Yoshida, A. Ichinose, S. Horii, A. Saito, and S. Ohshima: Selective preferred orientation control of $YBa_2Cu_3O_{7-\delta}$ films on a substrate, *Physica C*, **412-414** (2004) 1296-1300.

[7] J. L. Macmanus-Driscoll, S. R. Foltyn, Q. X. Jia, H.Wang, A. Serquis, L. Civale, B. Maiorov, M. E. Hawley, M. P. Maley, and D. E. Peterson: Strongly enhanced current densities in superconducting coated conductors of $YBa_2Cu_3O_{7-\delta}$ + $BaZrO_3$, *Nature Materials*, **3** (2004) 439-443.

[8] M. Mukaida, M. Ito, R. Kita, S. Horii, A. Ichinose, K. Matsumoto, Y. Yoshida, A. Saito, K. Koike, F. Hirose, and S. Ohshima: Reduction of surface resistance of $ErBa_2Cu_3O_{7-\delta}$ films by $BaZrO_3$ nano-particle inclusion, *Jpn. J. Appl. Phys. pt. 2*, **43** (2004) L1623-L1625.

[9] Y. Yoshida, K. Matsumoto, M. Miura, Y. Ichino, Y. Takai, A. Ichinose, S. Horii, and M. Mukaida: High-Critical-Current-Density $SmBa_2Cu_3$ O_{7-x} Films Induced by Surface Nanoparticle, *Jpn. J. Appl. Phys.*, **44** (2005) L546-L548.

[10] P. Mele, K. Matsumoto, T. Horide, A. Ichinose, M. Mukaida, Y. Yoshida, S. Horii, and R. Kita: Ultra-high flux pinning properties of $BaMO_3$-doped $YBa_2Cu_3O_{7-x}$ thin films (M=Zr, Sn), *Supercond. Sci. Technol.*, **21** (2008) 32002.

[11] M. Mukaida, M. Kusunoki, and S. Ohshima: Growth manners of *c*-axis oriented $YBa_2Cu_3O_x$ thin films, *Advances in Superconductivity*, **11** (1999) 1019-1022.

[12] J. E. Gruzlesk and W. C. Winegard: Fault structure in lamellar eutectics, *J. of the Inst. of Metals*, **96** (1968) 301.